Neutron lifetime measurements using gravitationally trapped ultracold neutrons *)

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Abstract

Experiment using gravitationally trapped ultracold neutrons (UCNs) to measure the neutron lifetime is reviewed. The precise value of the neutron lifetime is of fundamental importance to particle physics and cosmology. In our experiment, the UCN storage time is brought closest ever to the neutron lifetime: the probability of the UCN loss from the trap was only 1% of that for neutron β-decay. The neutron lifetime obtained, $878.5 \pm 0.7_{stat} \pm 0.3_{sys}$ s, is the most accurate one to date

*) In connection with increasing the interest to details of our experiment we are publishing here the extended version of our first PNPI preprint #2564 (2004) prepared before short publication in Phys. Lett. B **605** (2005) 72-78.

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1. Introduction

The problem of precise measurements of the neutron lifetime is important for elementary particle physics and cosmology. The decay of a free neutron into a proton, an electron, and an antineutrino is determined by the weak interaction comprising the transition of a d-quark into a u-quark. In the Standard Model of elementary particles, the quark mixing is described by the Cabibbo - Kobayashi - Maskawa (CKM) matrix which must be unitary. For instance, for the first row we have

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1, \qquad (1.1)$$

where V_{ud}, V_{us}, V_{ub}, are the matrix elements responsible for the mixing of a u-quark with a d-, s-, or b-quark, respectively. The values of the individual matrix elements are determined by the weak decays of the respective quarks. In particular, the matrix element V_{ud} can be determined from the data on nuclear β-decay and neutron β-decay. The extraction of V_{ud} from the data on neutron β-decay is extremely tempting due to the theoretical simplicity of describing the neutron decay compared to the description of nuclear decay. Unfortunately, the experimental procedure is a very complicated one, since it requires precise measurements of the neutron lifetime τ_n and the β-decay asymmetry A_0. The neutron half-life t is given by the following equation [1]

$$ft(1+\delta'_R) = \frac{k}{|V_{ud}|^2 \, G_F{}^2 (1+3\lambda^2)(1+\Delta_R)}, \qquad (1.2)$$

where f =1.6886 is the phase space factor, δ'_R=1.466×10^{-2} is a model-independent external radiative correction calculated with an accuracy of 9·10^{-5} [2,3]; Δ_R=2.40×10^{-2} is a model-dependent internal radiative correction calculated with an accuracy of 8×10^{-4} [4,5]; λ - is the ratio of the axial-vector weak coupling constant to the vector weak coupling constant, $\lambda = G_A / G_V$, G_F is the Fermi weak coupling constant determined from the μ-decay, and K $K = \hbar(2\pi^3 \ln 2)(\hbar c)^6 / (m_e c^2)^5$.

The general formula for calculating $|V_{ud}|^2$ on the basis of the data on neutron β-decay has the form [1, 3]

$$|V_{ud}|^2 = \frac{4908 \pm 4\, сек}{\tau_n (1+3\lambda^2)} \quad , \qquad (1.3)$$

where the inaccuracy in calculations of the radiative corrections was taken into account. Thus, the required relative accuracy of measuring the neutron lifetime τ_n must be higher than 10^{-3}, while the relative accuracy of measuring λ must be higher than $0.5 \cdot 10^{-3}$. The parameter λ is found from measurements of the asymmetry A_0 of neutron β-decay:

$$A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}. \qquad (1.4)$$

Since $\Delta\lambda / \lambda = 0,25 \Delta A_0 / A_0$, the relative accuracy of measuring the A-asymmetry must be higher than $2 \cdot 10^{-3}$.

Precise measurements of the neutron lifetime are also critically important when one wishes to verify a model of the early stages of the formation of the Universe.

The observed quantities in the Big Bang model are the initial abundances of deuterium and ^{4}He. These depend on the ratio of the number of baryons to the number of photons in the initial nucleosynthesis stage and on the neutron lifetime τ_n. For instance, at a fixed value of baryon asymmetry η_{10}, a variation in the neutron lifetime by 1% changes the value of the initial abundance of ^{4}He by 0.75%. The relative accuracy of measurement of the helium-4 abundance comprises ±0.61% [7]. Similarly, a variation in the neutron lifetime by 1% changes η_{10} by 17%, although the modern accuracy of estimation of this quantity amounts to ±3.3% [7]. Thus, to verify the nucleosynthesis model in the Big Bang, the accuracy of measuring the neutron lifetime must be higher than 1%.

2. Experimental setup for measuring the neutron lifetime with a gravitational UCN trap and the measurement methods

2.1. Experimental setup

The experimental facility was a joint project of the B P Konstantinov Petersburg Nuclear Physics Institute (PNPI), Gatchina and the Joint Institute for Nuclear Research (JINR), Dubna. It was first used together with the universal source of cold and ultracold neutrons from the water-moderated water-cooled reactor VVR-M in Gatchina (Russia). At first, the cooling of the facility to 10-15 K was done by a refrigerator. Later, the facility was modernized (a cryostat scheme was utilized) and became self-contained, which made it possible to perform measurements that involved using the high-flux ILL reactor in Grenoble (France). Fig. 1 shows the modified version of the facility.

The facility comprises a gravitational trap for UCNs, but it can also serve as a differential gravitational spectrometer. Hence, a distinctive feature of this experimental setup is the possibility of measuring the UCN energy spectrum after the neutron has been stored in the trap.

The UCN storage trap 8 is placed inside the vacuum volume of the cryostat 9. The trap 8 has a window and can be rotated about the horizontal axis in such a way that the UCNs find themselves blocked by gravitational field in the trap when the window is in its uppermost position.

The ultracold neutrons enter the trap after traveling through the neutron guide 1, the open inlet valve 2, and the selector valve 3. The filling of the trap by the ultracold gas occurs when the trap window is in the 'down' position. After filling the trap, it is rotated so that the window appears to be in the 'up' position.

The vacuum system has two separate vacuum volumes: the 'high-vacuum' (6), and the 'isolating' (5). The pressure in the high-vacuum volume of the cryostat amounts to 5×10^{-6} mbar. At such a pressure, the residual gas only slightly affects the storage time (0.4 s; see Section 3.7) of the UCNs in the trap. Heat exchange between the trap and the cryostat's reservoir was used in the cooling of the trap. To improve the heat exchange, gaseous helium was blown through the vacuum volume of the cryostat and later removed before measuring the neutron lifetime.

The position (height) of the trap window in relation to the bottom of the trap determines the maximum energy of the UCNs that can be retained in the trap. Different values of the window height correspond to different values of the cutoff energy in the UCN spectrum; in other words, a rotating trap of this kind is a gravitational spectrometer. The spectral dependence of the neutron storage time can be measured through a series of rotations of the trap to the ‘window-down’ position. The trap was maintained in each intermediate position for 100 – 150 s to register the UCNs in the respective energy range. Using such a procedure, one can measure the spectrum of the trapped UCNs.

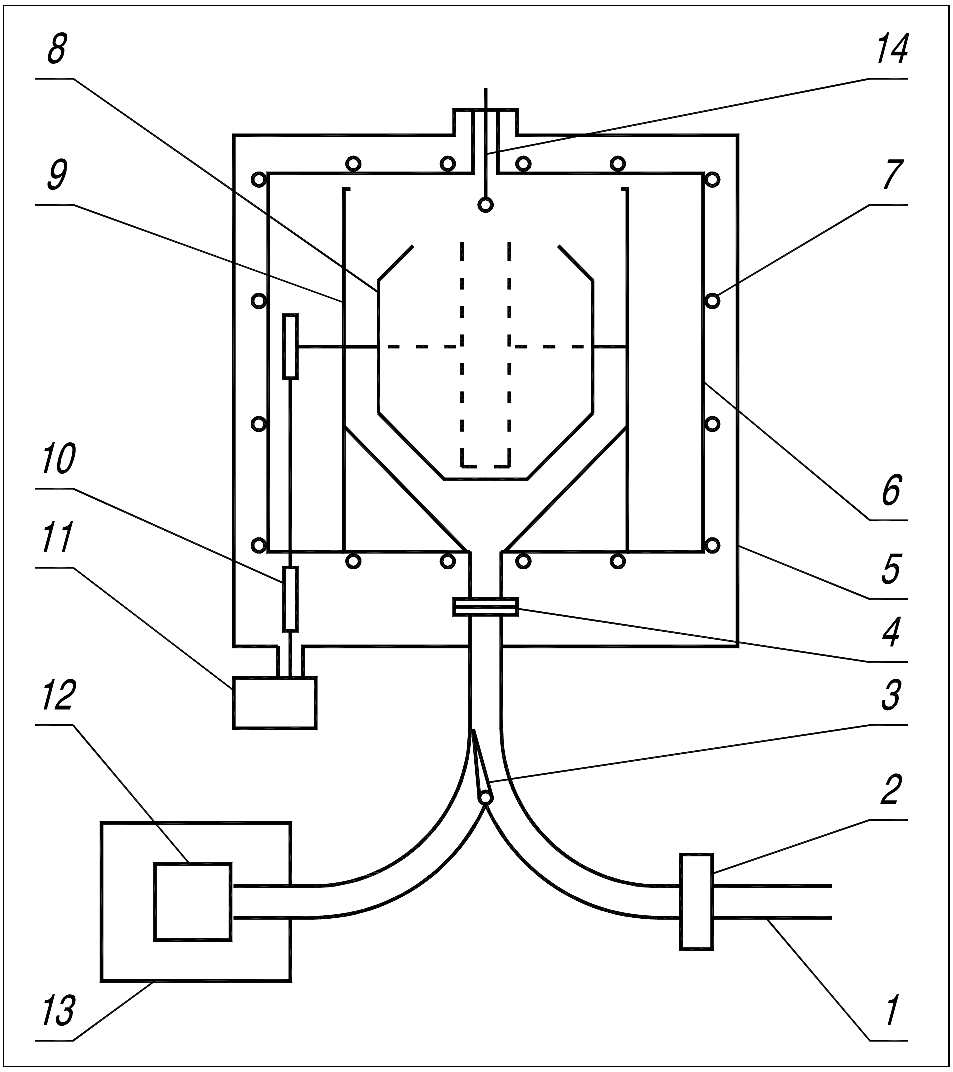

Figure 1. Schematic of the gravitational UCN storage system: 1, input neutron guide for UCNs; 2, inlet valve; 3, selector valve (shown in the position in which the trap is being filled with neutrons); 4, foil unit; 5, vacuum volume; 6, separate vacuum volume of the cryostat; 7, cooling system for the thermal shields; 8, UCN storage trap (the dashed lines depict a narrow cylindrical trap); 9, cryostat; 10, trap rotation drive; 11, step motor; 12, UCN detector; 13, detector shield, and 14, vaporizer.

The neutron lifetime was measured by the size extrapolation method. To this end, two UCN traps with different dimensions were employed. The first trap was quasispherical and consisted of a cylinder 26-cm high and 84 cm in diameter that was `crowned' by two truncated cones 22-cm high and 42 cm in diameter (the smaller diameter). The second trap was cylindrical, 14-cm high and 76 cm in diameter. The frequency of neutron collisions with the walls of the second trap was approximately 2.5 times higher than in the first trap. In Fig. 1, the narrow cylindrical trap is depicted by dashed lines.

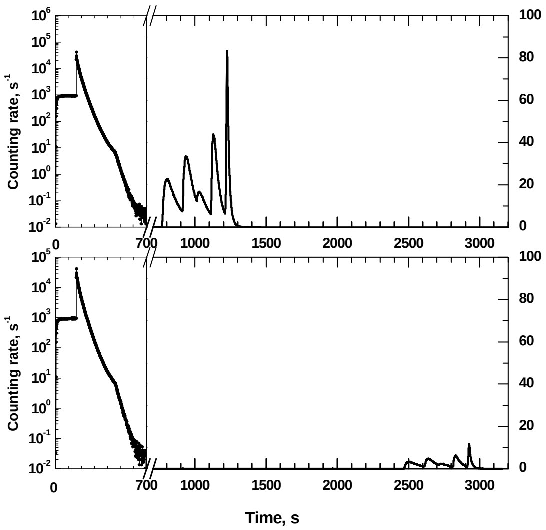

Figure 2. Time diagrams of the neutron storage cycle in a narrow trap for two different storage times.

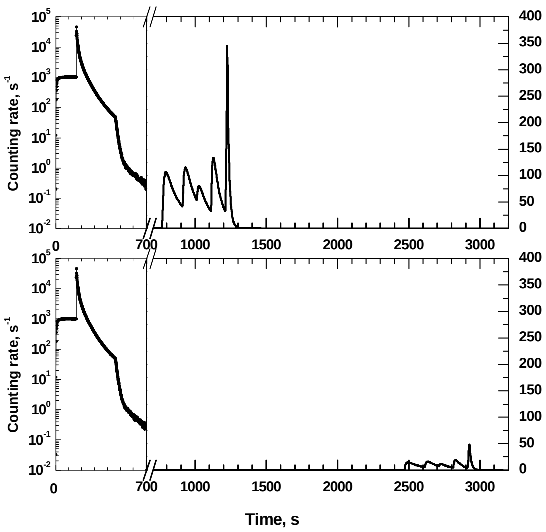

Figure 3. Time diagrams of the neutron storage cycle in a quasispherical trap for two different storage times.

A typical diagram of the counting rate at the detector in the measurement cycle with a narrow trap is shown in Fig. 2. (This diagram, built on the basis of the results of the latest experiments at ILL, differs predominantly from the previous diagrams in that the detector counting rate is higher.) Fig. 3 represents the similar time diagram, but for measurement cycle with a quasispherical trap.

At the beginning of a measurement cycle, the trap resides in the ‘window-down’ position, as it is being filled by UCNs. Then the trap is rotated into the monitoring position, in which the trap window height is approximately 10 cm lower than in the neutron storage position with its window ‘up’. The filling process can be monitored by the UCN detector 12 (see Fig. 1) through a slit in the selector valve. After the trap has been rotated into the monitoring position, the selector valve is switched into the position in which UCNs are registered. The trap is maintained in the monitoring position for 300 s. During this period, neutrons with energies higher than the gravitational barrier leave the trap (see Fig. 2). Then the trap is rotated into the storage position. The procedure of neutron capture and preparation of the UCN spectrum takes about 700 s; in the left part of Fig. 2 the counting rate is presented on the log scale, while the counting rate for the subsequent procedures (700 ± 3000 s) is presented with greater detail on the linear scale (the right part of Fig. 2). After a short (upper half of Fig. 2) or long (lower part of Fig. 2) storage time, the trap is rotated in step sequences through five positions, and in each of these positions it is kept motionless for 100 – 150 s, so the UCNs can be registered. The neutrons detected after each rotation have different mean energies. When all the UCNs have left the trap, the background count rate is measured. The angular positions of the trap window and the mean values of the UCN energies in each discharge are as follows:

$\theta = 30^o$ (monitoring position);
$\theta = 40^o$, $E_{UCN} = 58$ cm;
$\theta = 50^o$, $E_{UCN} = 52$ cm;
$\theta = 60^o$, $E_{UCN} = 46$ cm;
$\theta = 75^o$, $E_{UCN} = 39$ cm;
$\theta = 180^o$, $E_{UCN} = 25$ cm.

The angles were chosen in such a way that there would be an equal number of UCNs for each segment of the UCN spectrum (unfortunately, the third portion was not success-fully optimized, which is clearly obvious from Fig. 2).

2.2. Methods of extrapolation to the neutron lifetime. Basic relations

Any measurement of the neutron lifetime that follows the UCN storage method is based on the simple equation

$$\tau_{st}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1} \tag{2.1}$$

Here, the total UCN loss probability τ_{st}^{-1} comprises two terms, namely, the probability of neutron β-decay τ_n^{-1}, and the probability τ_{loss}^{-1} of other possible UCN losses.

The UCN storage time τ_{st}^{-1} can be calculated if we know the measured number of neutrons that remain in the trap after two different storage times:

$$\tau_{st} = \frac{t_2 - t_1}{ln(N_1/N_2)} \ , \tag{2.2}$$

where N_1 and N_2 are the numbers of neutrons left in the trap after storage times t_1 and t_2, respectively. There is no need to know the efficiency of the UCN detector, the probability of UCN losses as the neutrons travel along the neutron guide, and so forth, since equation (2.2) uses only the ratio of the numbers of neutrons.

Since the UCNs are stored in a material trap, τ_{loss}^{-1} contains the probability of loss at the trap walls:

$$\tau_{loss}^{-1} = \mu(T,E) \cdot \nu(E) \qquad (2.3)$$

where $\mu(T,E)$ is the function of UCN losses due to reflection, which depends on the UCN energy and the temperature of the trap walls, and ν is the collision frequency of the UCNs with the trap walls, which depends on the UCN energy and the trap dimension. The function of UCN losses due to reflection, obtained on the assumption that the UCNs are reflected from a potential step with real (U_0) and imaginary (W) parts, can be represented in the following well-known form [10]

$$\mu(y) = \frac{2\eta}{y^2} \cdot (\arcsin y - y\sqrt{1-y^2}) \begin{cases} \approx \pi\eta, & y \to 1 \\ \approx \frac{4}{3}\eta y, & y << 1 \end{cases} \qquad (2.4)$$

where η is the loss factor determined by the ratio of the imaginary-to-real parts of the potential or the scattering amplitudes, $\eta = W/U_0 = b'/b$, and $y = (E/U_0)^{1/2}$.

In equation (3.4), the energy UCN loss function has been averaged over the incidence angles. Using the optical theorem, we can write down the imaginary part of the scattering amplitude in the following form [10]

$$b' = \frac{\sigma_{abs} + \sigma_{upscat}(T)}{2\lambda}.$$

The capture and inelastic-scattering cross sections are proportional to the neutron wavelength λ, with the result that neither b' nor η depend on λ or the neutron energy *E*. However, the loss factor is temperature-dependent, $\eta = \eta(T)$, due to the temperature dependence of the inelastic-scattering cross section $\sigma_{upscat}(T)$.

Now we can rewrite the right-hand side of equation (2.3) as the product of two factors: one depending only on the UCN energy, and the other only on the trap temperature:

$$\tau_{loss}^{-1} = \eta(T) \cdot \gamma(E) \qquad (2.5)$$

where $\eta(T)$ is the UCN energy-independent loss factor, and $\gamma(E)$ is the effective collision frequency which depends on the UCN energy and the trap dimensions. The neutron lifetime can be obtained via linear extrapolation of τ_{st}^{-1} to the zero value of γ. The UCN loss factor η proves to be equal to the tangent of the slope angle of the extrapolation line. Different values of the effective UCN collision frequency γ can be obtained by using traps of different dimensions and/or different values of the UCN energy. The effective frequency γ of UCN collisions with the trap walls can be computed.

2.3. The energy extrapolation method

To calculate the energy dependence of losses τ_{loss}^{-1} loss that allows for UCN motion in a gravitational field, a numerical integration method and the Monte Carlo method were employed. The loss probability was evaluated by the simple formula $\tau_{loss}^{-1} = \mu(E)\cdot\nu(E)$. The UCN collision frequency $\nu(E)$ is equal to the UCN flux directed onto a surface area dS, namely, $(1/4)\,\mathrm{v}\rho(\mathrm{v})dS$, where $\rho(\mathrm{v})$ is the UCN number density which depends on the UCN velocity v. In a gravitational field, the UCN number density is proportional to $\sqrt{(E-mgh)/E}$, where E is the UCN energy at the base of the trap, and h is the height measured from the base of the trap. Since the UCN kinetic energy depends on h, the above formula must be integrated with respect to h and then normalized:

$$\tau_{loss}^{-1}(E) = \frac{\int_0^E \mu(E-h')\cdot \mathrm{v}(E-h')\cdot \rho(E-h')dS(h)}{4\int_0^E \rho(E-h')dV(h)} \quad , \qquad (2.6)$$

where $h' = mgh$.

To compare the results produced by this formula with the experimental data, we must integrate it over the energy interval of each measurement and allow for the real spectral distribution of the UCN number density in the trap. The UCN spectrum in the trap was measured immediately after completion of the monitoring process by the procedure reproduced in the upper part of Fig. 2. We also allowed for modifications of the spectrum during UCN storage in the trap, the factor of which provides a small correction to the computed function γ ($\Delta\gamma/\gamma = 0.1\%$ or 0.01 s for the extrapolated neutron lifetime). Additional corrections to the computed function γ were also made, so as to take into account the incomplete discharge of UCNs for each energy interval, as Fig. 2 implies. This may produce a correction up to 0.7 s in the extrapolated neutron lifetime. However, using the results of detailed numerical simulations by the Monte Carlo method and the size extrapolation method (see Section 3.6), we can reduce this correction and obtain an uncertainty in the extrapolation to the neutron lifetime amounting to about 0.24 s.

Using the calculated values of the loss factor for different energies, $\tau_{loss}^{-1} = \eta(T)\cdot\gamma(E)$, we can extrapolate the measurement data and find the neutron lifetime. The result of such an extrapolation depends on the function $\mu(E)$ which actually may differ somewhat from that of the adopted form (2.4), for example, it can be specified by a certain function $\mu'(E)$. To reduce the systematic effect caused by the uncertainty in the energy dependence $\mu'(E)$, we must examine the possibility of excluding the effect of the energy dependence of the loss factor on the extrapolation results.

2.4. The size extrapolation method

To exclude the effect of the energy dependence $\mu'(E)$ on the result, we can make extrapolation to zero losses by using data on the storage of UCNs with the same mean energy in traps of different dimensions. Using relationships (2.1) and (2.5) for two traps with storage times τ_1 and τ_2, namely

$$\tau_1^{-1}(E) = \tau_n^{-1} + \eta\gamma_1(E) \tag{2.7}$$

$$\tau_2^{-1}(E) = \tau_n^{-1} + \eta\gamma_2(E) \tag{2.8}$$

we find that

$$\tau_n^{-1} = \tau_1^{-1}(E) - \frac{\tau_2^{-1}(E) - \tau_1^{-1}(E)}{\gamma_2(E)/\gamma_1(E) - 1} \tag{2.9}$$

Thus, the effect of the energy dependence $\mu'(E)$ is excluded almost entirely because the final result for the neutron lifetime depends only on the ratio $\gamma_2(E)/\gamma_1(E)$. Clearly, in the absence of gravitation, by employing equations (2.7) and (2.8) for two different traps and a certain energy we can totally exclude the function $\mu'(E)$. In reality, where there is gravitation, complete exclusion of $\mu'(E)$ is impossible because of the integral equation (2.6). However, the residual effect of the dependence $\mu'(E)$ on the neutron lifetime was negligible. For instance, in our last experiment the contribution from this dependence amounted to 0.14 s, while the statistical accuracy of the measurements was 0.7 s. The size extrapolation method based on the idea of using two traps makes it possible to substantially reduce systematic errors which are caused by the uncertainty of our knowledge about the function $\mu'(E)$.

3. Neutron lifetime measurements using a gravitational UCN trap coated with LT Fomblin oil

3.1. Low-temperature Fomblin oil

In the experiment, a new type of material, low-temperature(LT) Fomblin oil, was used for coating trap walls. This was deposited on the trap surface by evaporation in a vacuum. The oil (Fomblin) contains only C, O, and F, so that the neutron-capture cross section for it is small. As a result of a preliminary study of several types of LT Fomblin it was found [11] that the quasielastic and inelastic UCN scattering in LT Fomblin for T < –120˚C is much weaker than in ordinary Fomblin at room temperature. Quasielastic UCN scattering is completely suppressed for T < –120˚C [11], and because of neutron inelastic scattering the expected UCN loss factor η amounts to roughly $2\cdot10^{-6}$ [12].

The new type of LT Fomblin used in the experiment has a molecular mass M = 2354 u and a vapor pressure $P = 1.5\cdot10^{-3}$ mbar at room temperature. Prior to beginning the LT Fomblin deposition procedure, a spherical vaporizer with tiny holes was heated to 140˚C by an electric heater. Then gaseous helium was utilized to force three cubic centimeters of Fomblin oil into the vaporizer's chamber along a vertical tube. The deposition of LT

Fomblin amounted to evaporating Fomblin and freezing it, after which it settled on the inner walls of the trap cooled to –150˚C. To achieve homogeneity, the vaporizer was moved up and down.

3.2. Studying the coating properties of LT Fomblin oil

In order to check the quality of the oil film, a copper trap with a titanium coating was employed. Titanium has a negative scattering length and does not generate a reflecting potential for UCNs. Ultracold neutrons cannot be stored in such a trap if the titanium coating is not covered by a layer of Fomblin. The trap was a 50-cm long cylinder with a diameter of 76 cm. The stable storage time $\tau_{st} = 869.0 \pm 0.5$ s was achieved after several depositions of LT Fomblin (the total thickness amounted to 15 µm) with the temperature of the trap walls varying from –140 to –150˚C and after a single heating – cooling cycle in which the trap temperature was first raised to room temperature and then brought down to T = –160˚C. Repetition of the thermal cycling had no effect on the UCN storage time in the trap. It is quite possible that at room temperature the oil filled all the gaps and cracks in the trap walls and formed a perfect surface. In addition, LT Fomblin was degassed in the thin layer at room temperature. Such a coating is extremely stable, and no essential variation in the storage time was detected during the eight-day period of observation. Subsequent depositions had no effect on the value of the UCN storage time in the trap.

The traps used in the final measurements were coated with beryllium (a quasispherical trap and a narrow cylindrical trap). Since beryllium constitutes a good reflector of ultracold neutrons, the trap walls can be cooled to even lower temperatures, since the appearance of any microcracks in the coating have a small influence on the UCN lifetime in the trap. Using a beryllium-coated trap, we studied the temperature dependence of the storage time for a quasispherical trap coated with LT Fomblin (Fig. 4a).

LT Fomblin oil was frozen on the trap wall at T = –155˚C, then the trap was slowly heated up to T = –50˚C, and finally cooled down again to T = –160˚C. In this way, we covered up the layer defects with oil when it was fairly liquid. After this temperature cycling was completed, the measured storage time turned out to be longer, 872.2 ± 0.3 s, than immediately after sputtering (850 ± 1.8 s). Repeated warming and cooling cycles didn't change the UCN storage time of traps (see Fig. 7).

This procedure (heating after evaporation at T = –160˚C) is extremely important because the oil in liquid form coat all defects of surface due to effect of the surface tension of oil.

Comparing the storage time of trap with titanium substrate and with beryllium substrate we can estimate the part of uncoated by LTF surface. Bearing in mind that the titanium and beryllium traps differed in dimensions, we calculated the difference between the expected and measured storage times for the titanium trap, which was 1.9 ± 0.6 s. This is equivalent to the uncovered part of the surface area of the titanium trap amounting only to $(4.4 \pm 1.3)\times10^{-7}$. Hence, the reproducible LT Fomblin coating can be obtained irrespective of the material and shape of the trap. For this reason, there is no need to examine the different loss factors η for various traps with a beryllium sublayer under LT Fomblin coating.

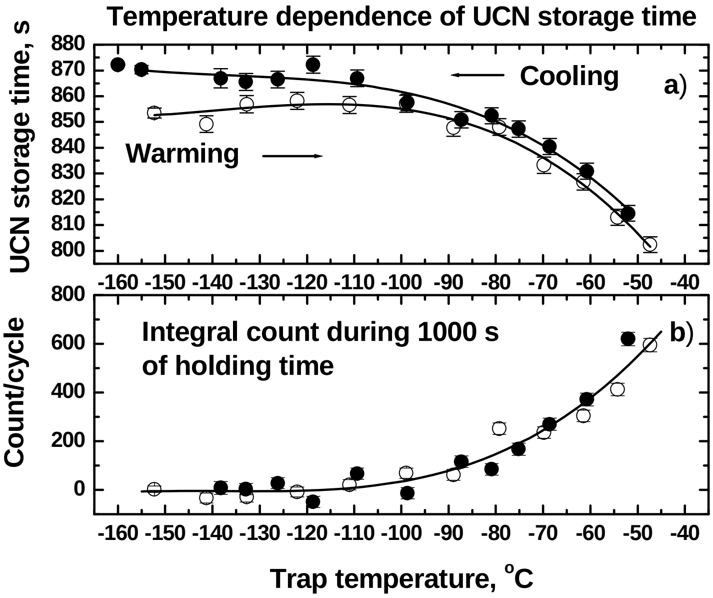

Figure 4. Temperature dependence of (a) the UCN storage time in the course of cooling and heating after the first evaporation of LTF oil at T = –155˚C, and (b) the integral count for a 1000-s storage period.

3.3. Studying the quasielastic UCN scattering

In the course of investigations that used a beryllium-coated trap, the quasielastic UCN scattering by LT Fomblin was studied.

In our installation we used the principle of gravitational valve. The particularity of the gravitational valve is that it can not storage the UCN with energy more than gravitational barrier. If UCN during the storage take up additional energy they will leave the trap and reach the detector.

Figure 4b shows the number of ultracold neutrons that leave the trap during a 1000-s storage period, as a function of the trap temperature. In the process, there was observed an additional (in relation to the background noise) counting rate which fell off exponentially with the passage of the time of UCN storage in the trap. The additional counting rate appears because the UCNs acquire energy in their quasielastic scattering by LT Fomblin. These neutrons leave the trap, which drives the counting rate at the detector up. The counting of quasielastically scattered UCNs becomes indistinguishable against the background (i.e., disappears) as T < –120˚C. This result is in qualitative agreement with that of measuring the quasielastic UCN scattering by LT Fomblin, studied in our previous work [11].

Here, this process was studied in the more details, particularly at the temperature T = –160˚C. At the temperature T = –60˚C we find the reasonable agreement with result of work [11]. Illustration of process of UCN upscattering at the temperature T = –60˚C is shown in Fig. 5. We can see the clear definite exponent with UCN storage time in the trap.

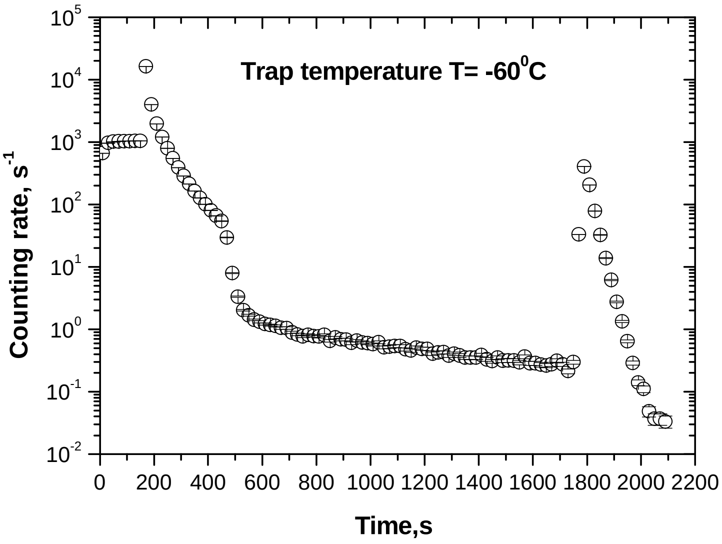

Figure 5. Time diagram of the neutron storage cycle in a quasispherical trap at T = –60˚C.

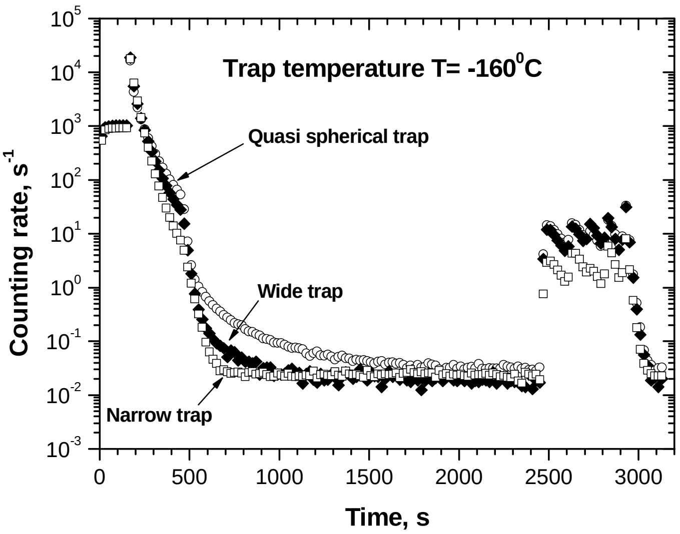

Figure 6. Time diagram of the neutron storage cycle in a narrow cylindrical, wide cylindrical and quasi-spherical trap at T = –160˚C.

The most important studies have been carried out at the trap temperature T = –160˚C. Figure 6 shows the counting rate of detector during UCN storage in the traps with temperature T = –160˚C. Just after rotation of trap in the storage position – hole up – we can see the process of UCN leakage with energy above gravitational barrier. The exponential time is different for different traps (narrow, wide cylindrical and quasi-spherical) because of different ratio of window square to the trap volume. The exponential times of leakage are in reasonable agreement with Monte-Carlo calculations. For the narrow trap this process is the most fast – about 30 s, therefore this curve is the most preferable for analysis of UCN upscattering. The analysis shows that there is no any UCN leakage with exponential time like the storage time – about 800÷850 s. We can install only upper limit for probability of UCN upscattering with energy transfer about 20 neV. This upper limit is 6×10^{-9} per one collision. From this upper limit of UCN probability of leakage at storage in the trap we can install also the upper limit of correction to neutron lifetime, which is less than 0.03 s. It should be mentioned that the estimation is valid for any process of low energy transfer due to interaction with trap surface as well as interaction inside the trap volume.

Thus, it turned out that for T < –120˚C quasielastic UCN scattering could be ignored. Our measurements were done at T = –160˚C to guarantee that quasielastic scattering does not affect the results.

3.4. Studying of the stability and reproducibility of coating

The stability and integrity of the coatings on various traps constitute the most important conditions for the use of the size extrapolation method in measuring the neutron lifetime. Therefore, the quality of the LT Fomblin coating was checked many times during measurements. Figure 7 gives eight results of measurements of the neutron storage time for a quasispherical trap, and seven analogous results for a narrow trap. The measurements were carried out after new depositions, heating, and cooling with a subsequent new deposition, etc. After a liquid-helium cryogenic pump was mounted near the storage volume, the trap's vacuum was improved from 5×10^{-6} to 3×10^{-7} mbar. The storage times during the experiment on measuring the neutron lifetime agree, within approximately one second, for the wide trap and, within marginally broader limits, for the narrow trap. This proves that the LT Fomblin coatings are stable and reproducible for various traps.

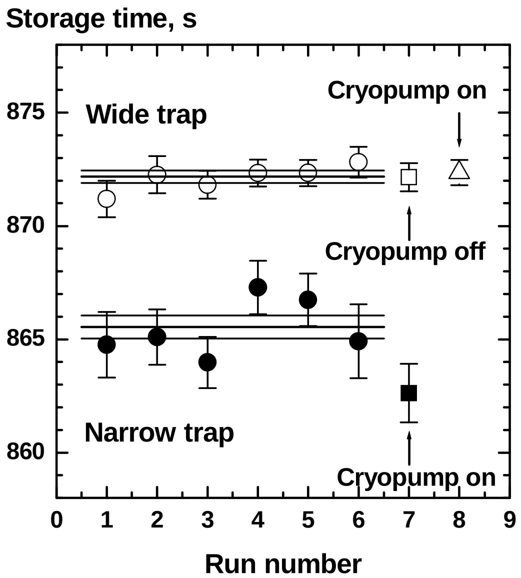

Figure 7. Demonstration of the stability of an LT Fomblin coating during measurements. The UCN storage times for the wide and narrow traps differ because of the different frequencies of UCN collisions with the trap walls.

Thus, basing our reasoning on the assumption that the substances used for coatings in various UCN traps were identical and taking into account the exceptionally high coating properties of a Fomblin oil, for which surface tension is responsible, and the absence of coating degradation, we believe that the same loss factor η can be used for different traps.

The level of statistical accuracy of our experiment agrees with the requirement that the loss factor η within about 5% is the same for different traps. However, test experiments have convinced us that this requirement is being met with a much higher accuracy.

3.5. Measurement data and extrapolation to the neutron lifetime

Figure 8 presents the results of measurements of the UCN storage times for various energy intervals and different traps (wide and narrow) as a function of the effective collision frequency γ. Extrapolation of all the data to the neutron lifetime yields a value of 877.60 ± 0.65 s at $\chi^2 = 0.95$, which means that combined extrapolation is possible. However, if we build an energy extrapolation for each trap and combine the two results, we get 875.55 ± 1.6 s.

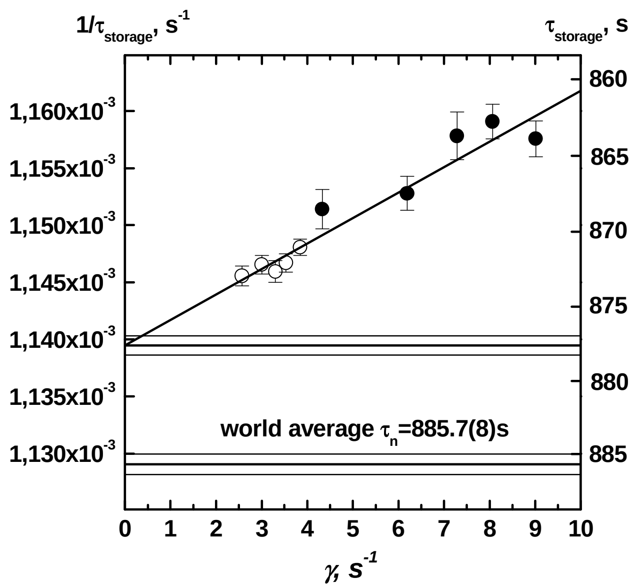

Figure 8. Result of extrapolation to the neutron lifetime when combined energy and size extrapolations are used. The open circles represent the results of measurements for a quasispherical trap, and the full circles the results of measurements for a cylindrical trap.

To use the size extrapolation method, we must combine the values obtained from different traps within the same UCN energy range and then calculate the average value of all the resultant values of the neutron lifetime.

Figure 9 demonstrates the results of size extrapolation to the neutron lifetime for different energy ranges. The average value of the neutron lifetime obtained by the size extrapolation method was 878.07 ± 0.73 s.

The results corresponding to these two methods differ by 1.5σ. The loss factor obtained in this experiment, $\eta = 2\times10^{-6}$, agrees with the value found in the transmission experiment [12]. For the final value of the neutron lifetime we prefer using the result of size extrapolation, which depends rather weakly on $\mu(E)$ and which we consider more reliable.

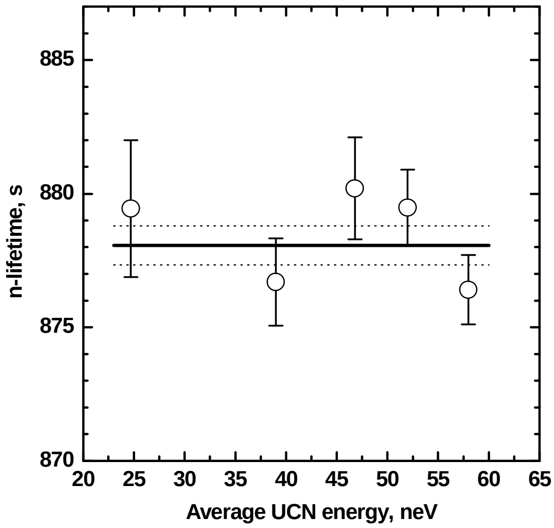

Figure 9. Extrapolated values of the neutron lifetime for different mean UCN energies, when size extrapolation is used. The solid straight line corresponds to the average value of neutron lifetime for given measurements.

3.6. Monte Carlo simulation of the experiment and systematic errors

To estimate the accuracy and to test the reliability of the size extrapolation method in which the value of the function γ must be calculated, we did a simulation of the experiment by using the Monte Carlo method.

The adopted Monte Carlo model describes the behavior of neutrons with allowance for a gravitational field, the shape of the storage traps, trap losses η = 2×10^{-6}, and the geometries of the secondary volume and the ultracold neutron guide. As a result, we were able to directly simulate the measurement procedure and to build a time diagram for the counting rate at the detector, similar to the one shown in Fig. 2. The times of UCN storage in traps and the extrapolations to the neutron lifetime that rely on the computed function g were calculated in the same way as in the experiment. The one adjustable parameter in the Monte Carlo model was the coefficient of UCN diffuse scattering in the interaction with the trap surface. All information about the probability of mirror reflection is extremely important. For instance, if it equals 99.9%, the behavior of UCNs in the trap becomes strongly correlated and predicting the result becomes extremely difficult.

Comparison of the results of Monte Carlo calculations for different values of the diffuse scattering probability and the experimental results (Fig. 10) makes it possible to conclude that the probability of UCN diffuse scattering by the LT Fomblin coating amounts to about 10%. In Fig. 10a we compare the experimental diagram and the Monte Carlo simulation diagram, obtained with the diffuse scattering coefficients equaling 10% and 100%. The experiment is successfully described for both diffusivity values. However, when the diffuse scattering probability is 0.1%, the agreement between the calculated and experimental results becomes unsatisfactory. The results of such calculations for the first part of the time diagram, which is most sensitive to neutron mirror reflection, are shown on a larger scale in Fig. 10b.

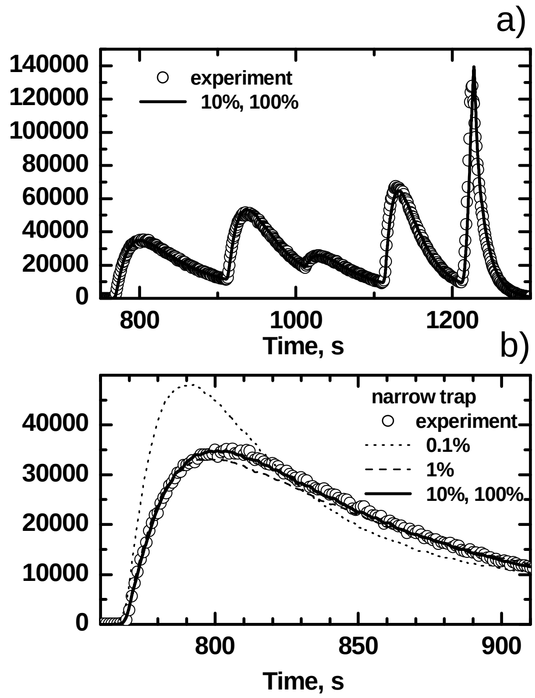

Figure 10. Simulation of an experiment by the Monte Carlo method, consisting in simulating the neutron discharge from a narrow cylindrical trap. The dotted curve corresponds to the results of calculations with a 0.1% diffuse reflection probability; the dashed curve corresponds to a 1% diffuse reflection probability, and the solid curve to 10% and 100%.

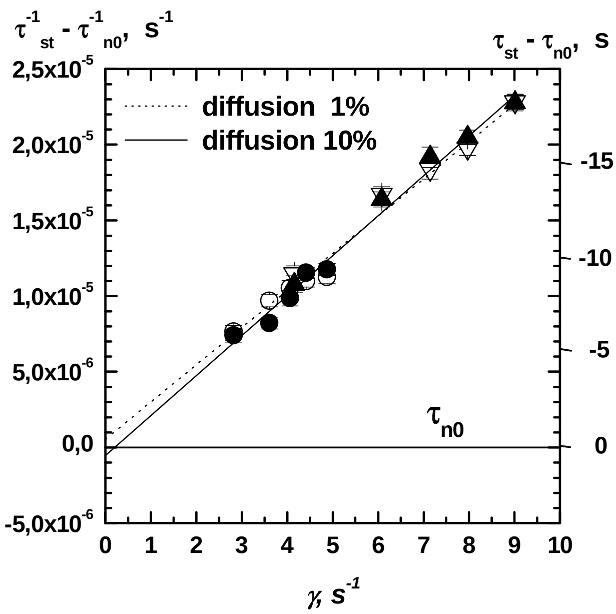

Figure 11. Monte Carlo experiment with a 1% and 10% diffuse reflection probability involving simulation of an extrapolation to the neutron lifetime.

The final simulation of the experiment was done for 10% and 1% diffuse reflection probabilities. The model storage times extrapolated to the neutron lifetime for the wide and narrow cylindrical traps and five different UCN energy ranges are presented in Fig. 11. To simplify the Monte Carlo calculations for the wide trap, we used cylindrical traps instead of quasispherical. In the final analysis of the data obtained with this model, we reproduced the value of the neutron lifetime adopted in the calculation with an accuracy of ± 0.236 s. This accuracy was limited by the statistical accuracy of the Monte Carlo calculations. Thus, because we employed the computed value of the function γ, the systematic uncertainty of the size extrapolation method amounted to ± 0.236 s.

It should be mentioned that Monte Carlo simulations with probability of diffusive scattering 0.1% have been carried out also. Fig. 12 demonstrates result of this simulation which is in visible disagreement with experimental plot, see Fig. 8. Therefore high mirror reflection did not take place in experiment.

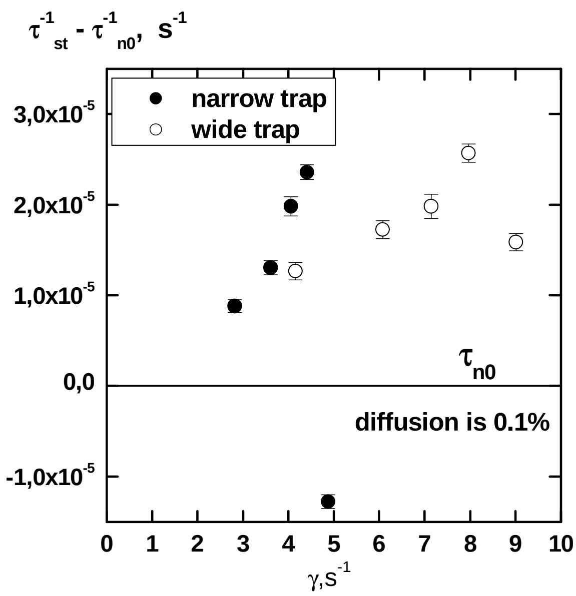

Figure 12. Monte Carlo experiment with a 0.1% diffuse reflection probability involving simulation of an extrapolation to the neutron lifetime. The full circles represent the results of simulation for a wide trap, and the open circles the results of simulation for a narrow cylindrical trap.

Another evidence of absence high mirror reflection comes from analysis of leakage process of above energy UCN from the trap just after beginning of storage process, which is shown in Fig. 13 for a narrow cylindrical trap and in Fig. 14 for a quasispherical trap. Monte Carlo simulation of this process shows that in case of high mirror reflection the tail of leakage process has to be considerably long. The results of experiment are consistent with the results of Monte Carlo simulation for diffuse reflection probability more than 1%.

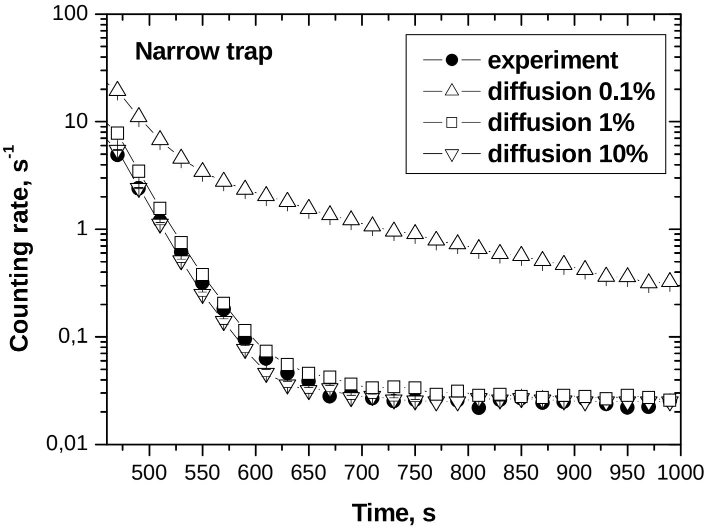

Figure 13. Monte Carlo simulation of leakage process of above energy UCN from the narrow cylindrical trap. The results of MC calculations with different diffuse reflection probability are presented: by up triangles with 0.1% diffusion, by squares with 1% diffusion and by down triangles with 10% diffusion. The filled circles represent the results of experiment.

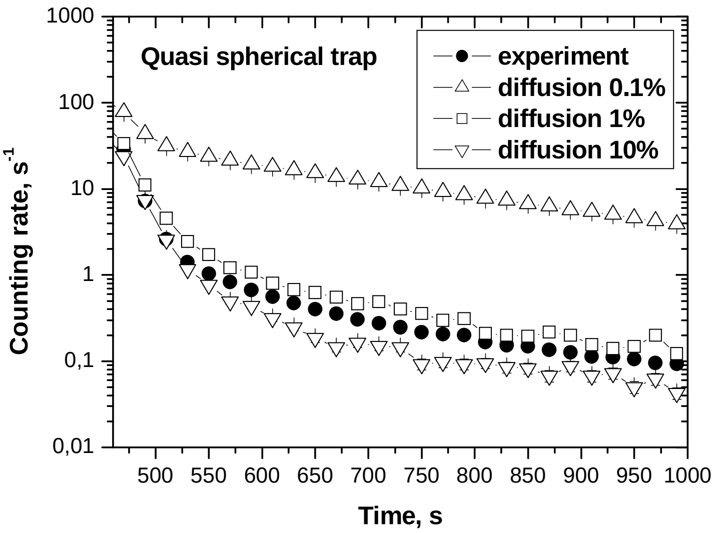

Figure 14. Monte Carlo simulation of leakage process of above energy UCN from the quasispherical trap. The results of MC calculations with different diffuse reflection probability are presented: by up triangles with 0.1% diffusion, by squares with 1% diffusion and by down triangles with 10% diffusion. The filled circles represent the results of experiment.

3.7. Effect of residual gas on UCN storage

When the neutron lifetime is measured with high precision, the effect of residual vacuum on the UCN loss cannot be ignored. For instance, a residual gas pressure of 5×10^{-6} mbar would introduce an error of about 1 s into the value of the UCN lifetime in the trap, which is comparable to the statistical accuracy of the measurements. Such a correction cannot be measured directly (for example, improving a vacuum pressure by an order of magnitude) because the expected effect is smaller than the statistical uncertainty. Instead, we increased the residual gas pressure to 8×10^{-4} mbar. This approach made it possible to measure the parameter $p\tau$ for the residual gas (9.5 mbar s) and obtain the calculated correction to the UCN lifetime in the trap, which amounted to 0.4 ± 0.02 s. This correction does not depend on the UCN energy and can be applied to refining the result for the neutron lifetime.

3.8. The final result for the neutron lifetime and a list of systematic corrections and errors

The magnitudes of the systematic effects and their uncertainties are listed in Table 3.

Table 3. Systematic effects and their uncertainties.

Systematic effect	Magnitude, s	Uncertainty, s
Method of calculating γ	0	0.236
Influence of shape of function $\mu(E)$	0	0.144
UCN spectrum uncertainty	0	0.104
Uncertainty of trap dimensions (1 mm)	0	0.058
Residual gas effect	0.4	0.024
Uncertainty in LT Fomblin critical energy (20 neV)	0	0.004
Total systematic correction	0.4	0.3

The main contribution to the uncertainty is provided by the statistical accuracy of determining the UCN lifetime. The next (by value) uncertainty is that in the calculation of the function γ. The contributions from the uncertainty of the shape of the function $\mu(E)$ and the uncertainty in the UCN spectrum, which are much smaller, were estimated by varying their parameters within the uncertainty limits allowed by the experimental data. Thus, the total systematic correction proved to be equal to 0.4 ± 0.3 s, and the final result for the neutron lifetime amounted to $878.5 \pm 0.7_{stat} \pm 0.3_{sys}$ s.

4. Reasons for the discrepancy between the results of experiments on UCN storage

The new result for the neutron lifetime differs from the world average value by 6.5σ, although actually this deviation is determined mainly by the discrepancy between our result and the result of the experiment done by Arzumanov et al. [6], who also achieved high precision in their measurements. The discrepancy with work [6] is 5.3σ. It is extremely difficult to discuss the reasons for this discrepancy. We are sure about the results of our experiment, since the probability of UCN losses amounts only to 1% of the probability of neutron β-decay, while in the experiment by Arzumanov et al. [6] the probability of UCN losses amounts to about 30%.

In our experiment we have extrapolation to neutron lifetime only 5 s from the best experimental storage time. In experiment [6] the task was to extrapolate about 120 s. It is not completely clear how to reach accuracy of extrapolation 0.4 s using two experimental storage times (approximately 765 s and 555 s) for two configurations of UCN trap with different neutron free path.

In our experiment, we used solid LT Fomblin, and the process of neutron quasielastic scattering was completely suppressed. Unfortunately, the experiment by Arzumanov et al. [6] was carried out before the effect of quasielastic scattering by liquid Fomblin was discovered, and the authors of Ref. [6] have to analyze the effect of quasielastic scattering on experimental results.

We are forced to note that in all the experiments involving liquid Fomblin [6, 8, 9], neutron quasielastic scattering was revealed and the process was found to change the spectrum during UCN storage. Although these experiments were run in the scaling mode, i.e., for traps of different dimensions the neutron containment time was chosen in such a way that the number of collisions was the same, the effect of spectrum change caused by quasielastic scattering was not taken into account. Our preliminary analysis shows that this effect may lead to an overestimated value of the neutron lifetime extrapolated.

At last we have to discuss discrepancy with our previous result which was obtained with solid oxygen coating of the trap. This discrepancy is not so big and is 2.7σ. Therefore we can not analyze the reason of this discrepancy; we can discuss the possible assumptions only. We can not exclude the possible contribution of anomalous losses with different energy dependence. Although the dependence of the final result on $\mu(E)$ is considerably suppressed when size extrapolation is used, in our previous experiment we used combined extrapolation in which the effect could have been suppressed to a lesser extent. Unfortunately, the level of statistical accuracy of the previous experiment makes an analysis of these assumptions impossible. Furthermore, it must be noted that the coating properties of solid oxygen are inferior to those of Fomblin oil. We can assume that quality of coating by solid oxygen was a little bit worse, because trap configuration is more difficult for coating. The portion of the uncoated surface for solid oxygen was approximately 10^{-2}, while that for Fomblin amounted to $(4.4 \pm 1.3)\times10^{-7}$. The most important problem of the equivalence of the coatings for the wide and narrow traps has been solved more reliably in our recent experiment which uses LT Fomblin.

Thus, our experiment with LT Fomblin possessed a very small loss factor. It also exhibited no effects of anomalous losses and neutron quasielastic scattering, in contrast to other experiments. All this guarantees the reliability of our results.

5. Conclusion

In conclusion we would like to summarize the main advantages of our experiment:

1. The storage time in the experiment is the most close to neutron lifetime. The probability of losses is about 1% of probability of neutron lifetime.

2. The extrapolated time from the best storage time is only 5 s, while the accuracy of extrapolation $\pm 0.7_{stat}$ s and $\pm 0.3_{sys}$ s. It means that relative accuracy of taking into account the losses in storage process is about 10% only.

3. The process of quasi-elastic scattering is completely suppressed. Upper limit for corrections of such type process is 0.03 s.

4. The coating properties of LT Fomblin oil are completely perfect. Uncovered part of surface has to be less than 10^{-6}. It gives the guarantee of the same loss factor for the different traps with beryllium substrate.

5. The stability and reproducibility of LT Fomblin coating was demonstrated in course of experiment.

All mentioned advantages of experiment allow to obtain the most precise result of neutron lifetime measurement: 878.5±0.8 s.

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